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Ultrafast Fiber Grating Sensor Systems for Velocity, Position, Pressure and Temperature Measurements

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ABSTRACT

In 2006 an approach was developed that used chirped fiber gratings in combination with a high speed read out configuration to measure the velocity and position of shock waves after detonation of energetic materials. The first demonstrations were conducted in 2007. Extensions of this technology were made to measure pressure and temperature as well as velocity and position during burn, deflagration and detonation. This paper reviews a series of improvements that have been made by Columbia Gorge Research, LLC, Lawrence Livermore National Lab and Los Alamos National Lab in developing and improving this technology.

Keywords: fiber grating, velocity, position, temperature, pressure, energetic material, high speed

INTRODUCTION

To model and characterize high speed energetic materials it is important to be able to measure velocity, position, pressure and temperature. By using chirped fiber gratings it is possible to measure these critical parameters on the surface, across boundaries and interior to a variety of materials during burn, deflagration and burn [1-11]. Initial demonstrations of velocity and position measurements were done at Lawrence Livermore National Labs with support of Columbia Gorge Research. The first demonstrations of pressure and temperature measurement capabilities were made using Russian DDT and card gap tests performed by Columbia Gorge Research under SBIR contracts W31P4Q-10-C-0187 and W31P4Q-11-C-0209 from the US Army at ATK Space Systems. Additional testing to demonstrate pressure measurements were made using impact testing [12] at Los Alamos National Lab. This has been followed by a new read out system approach at Los Alamos that allows full spectral scans of fiber gratings embedded in energetic material to be made at very high speeds. This paper provides an overview of development of the system from 2006 to 2016.

MEASUREMENT OF VELOCITY AND POSITION

The first issue addressed involved the determination the velocity and position of a shock wave during detonation of energetic material. The solution identified by Columbia Gorge Research used a chirped fiber grating similar to that shown in Figure 1. The unique character of this type of fiber grating is that the period varies along the length of it so that each region reflects a different wavelength. If the chirped fiber grating of Figure 1 is illuminated by a broad spectrum ASE light source then a broad spectrum is reflected with each position along the length of the chirped fiber grating wavelength encoded.

Figure 2 shows the spectrum of an ASE light source (blue curve) and the reflection from a chirped fiber grating it illuminates (green curve). A basic layout similar to that used to support early velocity and position measurements is shown in Figure 3. Here an ASE light source introduces light to a 3 port coupler with the second port directing light to the chirped fiber grating inserted into the test area. When the energetic material is detonated the chirped fiber grating is consumed and a portion of it is consumed. This reduces the intensity of the light reflected that in turn is directed toward the third port of the 3 port coupler and an output detector. The results are recorded on a high speed digital oscilloscope.

To verify the ability to measure position, at Lawrence Livermore a chirped fiber grating was cut back using a femto-second laser in small increments and the reflected spectrum measured by replacing the output detector of Figure 3 with an IMON 400 spectrometer. The result of this cut back tests is shown in Figure 4.

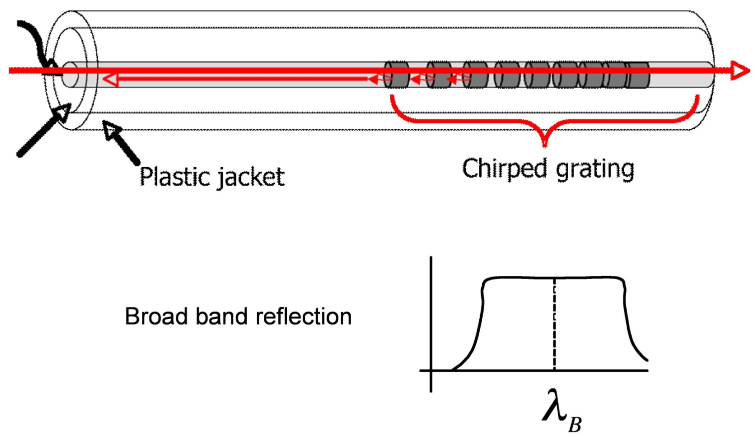

Figure 1. Chirped fiber grating that can be used to support velocity and position measurements in shock waves.

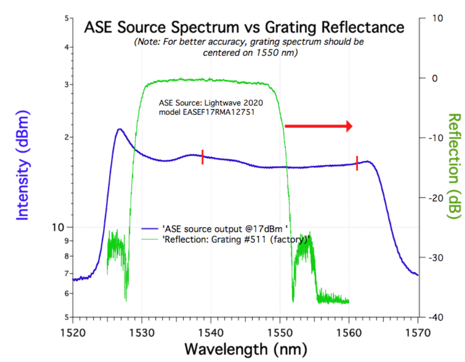

Figure 2 Spectral profile of a broadband ASE light source (blue line) used to illuminate a chirped fiber grating (reflected spectrum-green line)

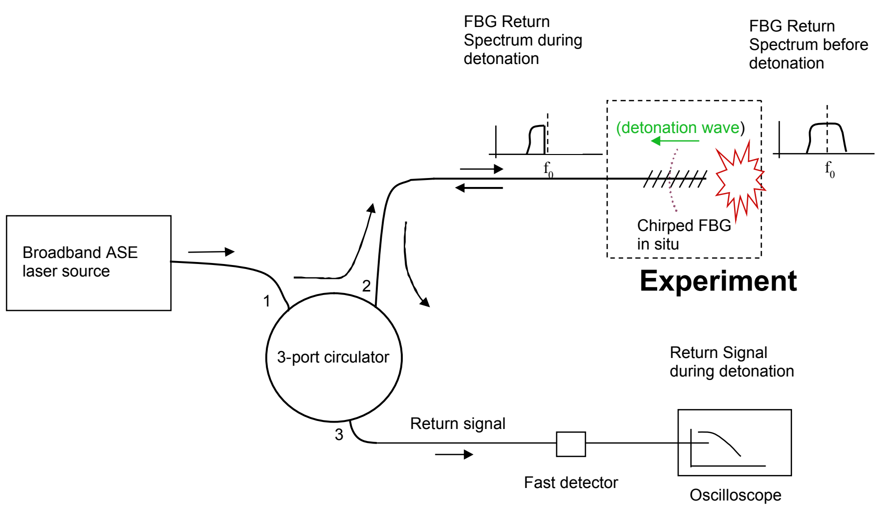

Figure 3 Basic block diagram of a system to measure the velocity and position of a shock front

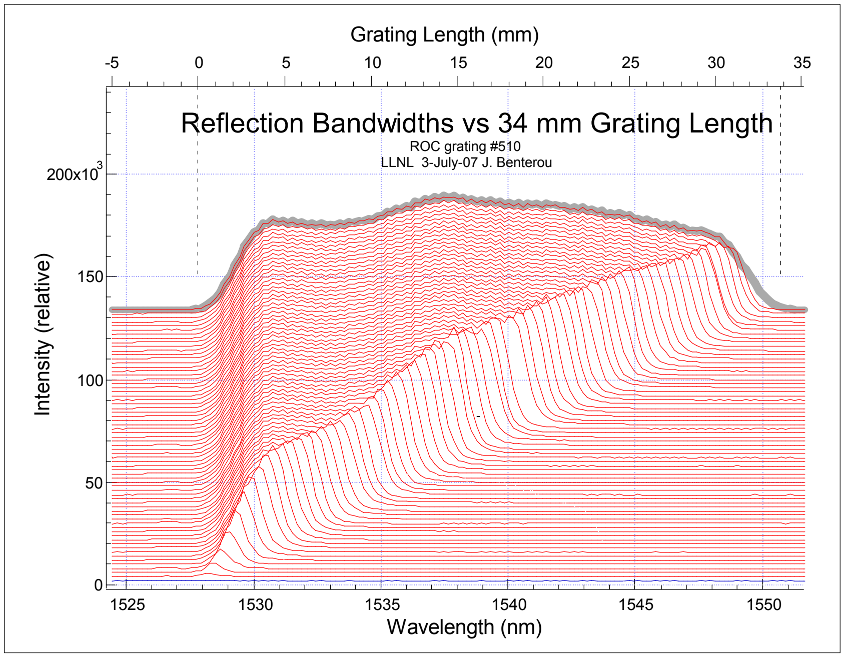

Figure 4. Changes in the reflected spectrum on a chirped fiber grating illuminated by and ASE light source as it is cut back to simulate the passage of a high intensity shock wave.

Figure 5 shows the result of a test a PBX-9502 sample with a Columbia Gorge Research read out system performed with Lawrence Livermore National Labs. The standard approach utilized before the introduction of this system used piezoelectric pins. When a shock wave passed the position of the shock wave registered as a voltage pulse. In Figure 5 there are five pins that will make five discrete position measurements that in turn can be converted into approximate velocity and position measurements. The chirped fiber grating approach, and the results associated with Figure 5 allow velocity and position to be measured along the entire length of the energetic material sample. These continuous velocity and position measurement capabilities at costs that are about the same as a few piezoelectric pins enabled the system to be economically viable at an early stage.

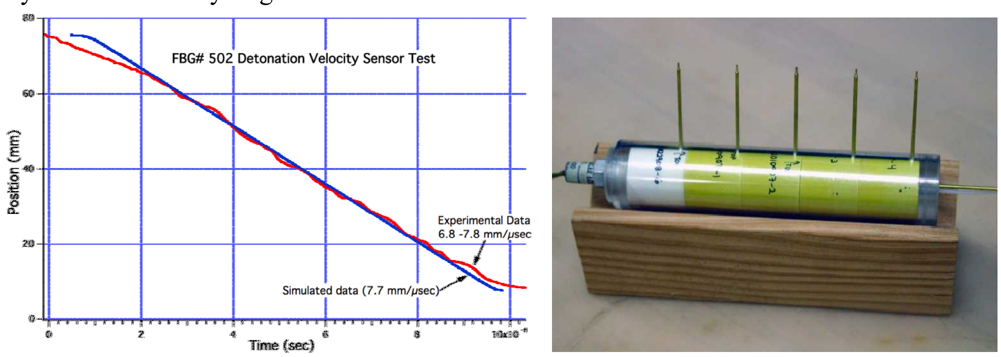

Figure 5 Measurement of position and velocity of a blast wave with a chirped fiber grating centered in a PBX-9502 test article (l25 mm in length and 25 mm in diameter)

Many early demonstrations of the power of this technique to measure velocity and position have been made at Lawrence Livermore and Los Alamos with the support of Columbia Gorge Research. One example performed at Lawrence Livermore is shown in Figures 6 and 7. Figure 6 shows a test block before and after ignition. A chirped fiber grating is placed at the edge of the block.

Figure 6 A chirped fiber grating is placed along the edge of a block with traces of energetic material designed to cause small detonations at the end of the block

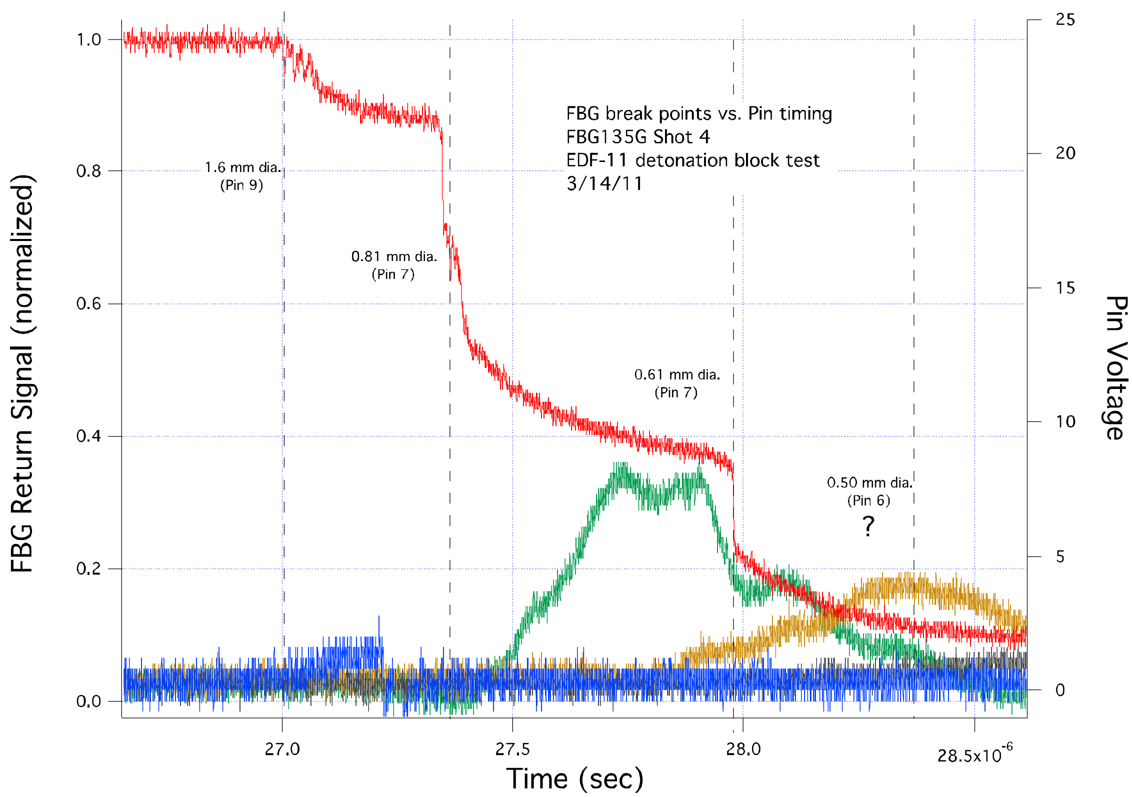

Figure 7 The red curve shows the response of the chirped fiber grating based optical system for the test block associated with Figure 6

ADDING PRESSURE AND TEMPERATURE MEASUREMENT CAPABILITIES

The ultimate goal of a system of this type is to measure pressure and temperature as well as velocity and pressure. The ideal case is to make these measurement continuously along the length of an optical fiber. There are a number of ways to approach this. Figure 8 shows the layout of a read out system based on high speed detectors in combination with filters. A broadband light source that may be an ASE light source is used to illuminate the fiber grating and the reflection from the fiber grating is directed back via a series of couplers. One leg of a 2x2 coupler is directed to an Ibsen Photonics IMON spectrometer that is used to measure the spectrum of the fiber grating before and after placement of the sensor on a test article. For fast events with an overall duration on the order of 10 to 100 microseconds the read out system is supported by a pair of 125 MHz detectors with a very low noise pre-amplification system that can measure rise times of approximately 5 nsec. A second detector can be used to record a data set with an optical filter placed in front of one of the detectors to aid in diagnostics.

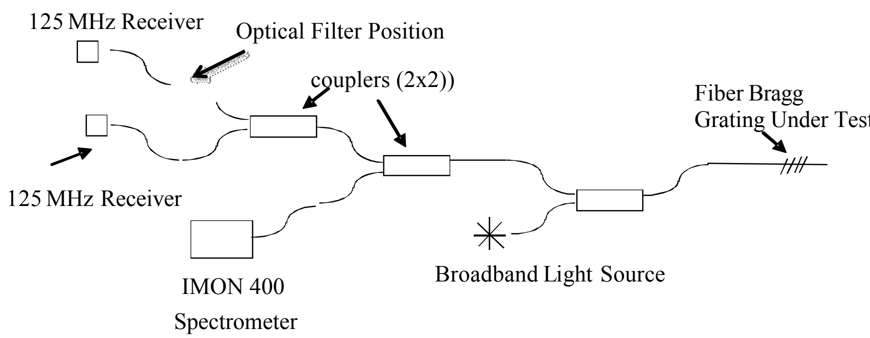

Figure 8 Block diagram of a read out system configured to support pressure and temperature measurements

For detonation events the velocity and position of the blast wave may be determined by monitoring the amplitude of the reflection from the chirped or uniform fiber gratings as they are consumed. This allows a continuous measurement to be made of velocity and position that is superior to that allowed by piezoelectric pins that give discrete point measurements as described in the prior section.

For events that are associated with a mixture of burn, deflagration and detonation the situation is more complex as spectral measurements are used while the fiber grating is intact to provide information about velocity, position, pressure and temperature.

There are a number of ways to extract information on pressure and temperature using filters; (1) the first is based on the spectral profile of the light illuminating the fiber grating, (2) the second involves modifications of the spectral profile itself, and (3) the third involves external filters that can be placed in several locations throughout the system including in front of the light source and in front of one or more detectors. As an example of the first approach, a broadband ASE light source has definite spectral features. Figure 9 shows the spectral profile of the ASE light source used to support testing. There is a spectral peak at 1528 nm with a width of about 5 nm, a rapid fall off of the spectra at about 1525 nm and an overall slope in the 1560 to 1535 nm region that can be used to support spectral measurements. When pressure is applied the fiber grating will contract and there will be an initial decrease in amplitude of the reflection signal as its spectra moves toward shorter wavelengths down the 1560 nm to 1535 nm slope. There will then be an increase in amplitude as it moves toward the 1528 nm peak followed by the decrease as it moves toward shorter wavelengths and falls off the 1525 nm spectral edge. Temperature increases the optical length of the fiber grating will drive its spectra toward longer wavelengths.

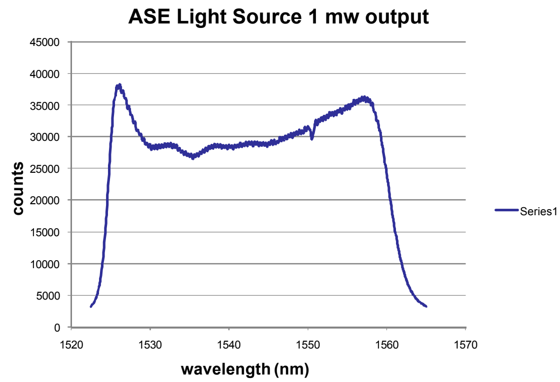

Figure 9 Spectral profile an ASE light source has features that act as a filter

Figure 10 shows the spectra of a custom chirped fiber grating sensor used to support the demonstration of pressure measurements during burn, deflagration and detonation associated with Russian DDT tests. This chirped fiber grating is 135 mm in length. It has a spectral width that spans from 1535 to 1562 nm. This fiber sensor uses conventional single mode optical fiber (Corning SMF-28) that does not have side-holes. For this type of fiber grating a 10,000 psi pressure change results in a shift of about 0.26 nm. There are two spectral dips in the spectrum at 1552 and 1559 nm. These are formed by masking off 5 mm lengths of the 135 mm chirped fiber grating with a spacing of 20 mm. The marker gives a spatial position along the length of the fiber grating as well as a spectral measurement position.

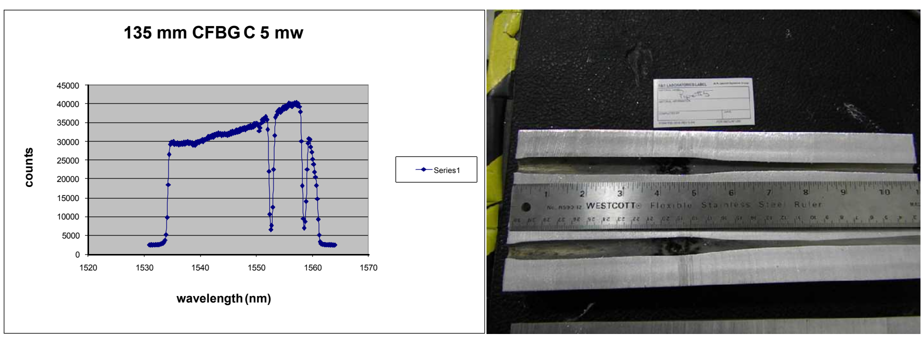

Figure 10 Spectrum of a 135 mm chirped fiber grating used to support a Russian DDT test. The photo of the cross sectioned pipe after firing shows the ignition end on the right, the uniform burn region, the expanded section associated with deflagration and the region associated with full detonation to the left. The optical lead exits to the left.

The Russian DDT test used consists of a 7.5 cm aluminum pipe that has a center hole of about 7 mm in diameter. The chirped fiber grating is insert is inserted into the center of the pipe which is then packed with energetic material. An igniter is placed on one end of the pipe. The unit is then inserted into a test fixture in a block house and fired. The photo on the right hand side of Figure 10 shows the cross sectioned pipe after firing. Ignition occurred on the right hand of the pipe and burn occurred increasing the pressure and temperature in this region. As burning progressed down the pipe a transition between burn and detonation known as deflagration occurred. The deflagration zone is an area of rapidly changing pressure and temperature. Finally detonation occurs resulting in the maximum pressure on the pipe. The pressure associated with each region can be determined by the expansion of the pipe walls.

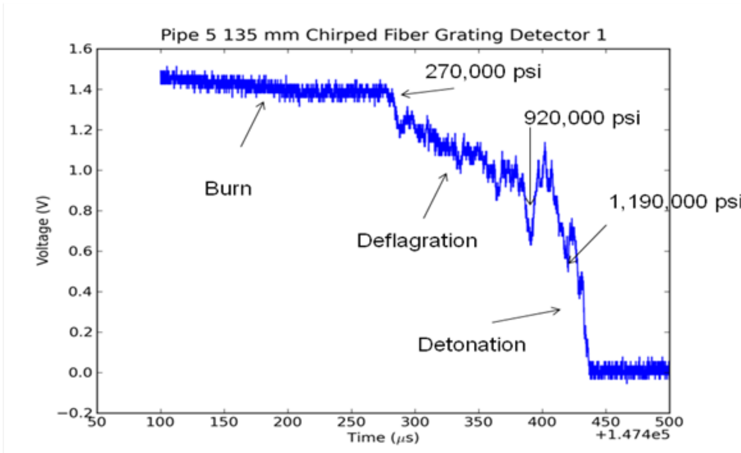

Figure 11 Test results for 135 mm chirped fiber grating in pipe of Figure 10

Figure 11 shows the test results from the 135 mm chirped fiber grating after ignition in pipe shown in Figure 10. During burn there is a slow pressure rise sufficient to drive the 1535 spectral "left" edge of the chirped fiber grating beyond 1528 nm corresponding to 270,000 psi. As burn increased there is an approximately linear increase in pressure over time until at about 180 microseconds the first marker dip at 1552 nm is driven over the edge of the ASE light source a shift of 24 nm or 920,000 psi. The second marker dip at 1559 nm occurs at about 215 microseconds and corresponds to a pressure of about 1,190,000 psi. At this point burn has transitioned to deflagration. The transition from deflagration to detonation occurs at about 1560 nm or 230 microseconds. This 32 nm shift corresponds to 1,230,000 psi.

Another approach to measuring pressure and temperature is to use optical fibers change birefringence with pressure. Two example of this type of optical fiber are conventional polarization maintaining optical fibers and side-hole optical fiber.

Figure 12 shows some examples of side hole optical fiber that have been used to support nearly static pressure measurements using fiber gratings. In both cases when pressure is applied to this side hole fiber grating system transverse forces will be applied to the fiber grating resulting in a spectral split that is proportional to pressure and nearly independent of temperature. As shown in Figure 13, when pressure is applied the single spectral peak splits into two. The peak to peak separation is a measure of pressure that is nearly independent of temperature (also shown in Figure 13). This temperature independence of the peak to peak separation is due to the two effective fiber gratings induced when transverse forces are applied across the core during pressure loading being collocated. To date temperature dependence of spectral peak splitting of this type of sensor has been beyond the ability of the best state of the art fiber grating read out units to measure.

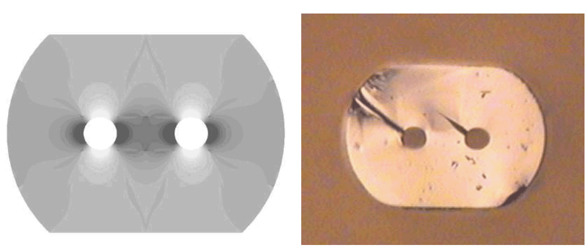

Figure 12 Side-hole optical fiber with fiber gratings written onto their core, has been used to support pressure measurements.

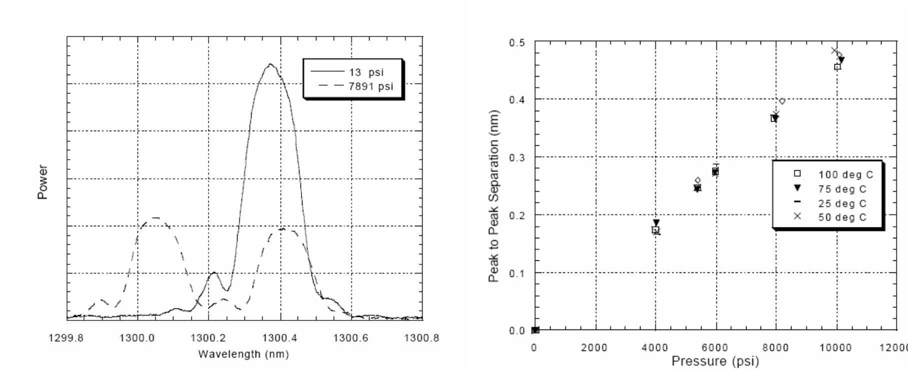

Figure 13. When pressure is applied to a fiber grating sensor written into side hole optical fiber a spectral split proportional to pressure and nearly independent of temperature results. Temperature may be measured by the overall shift in the spectral profile.

To measure temperature the overall shift of the dual peak spectral profile of the side hole optical fiber is measured.

It is also possible to measure pressure or temperature with a fiber grating written onto conventional optical fiber provided that there is variation of only one parameter at a time. Figure 14 shows the spectral peak to peak separation of 125 micron diameter optical fiber with 30 micron side holes as well as the mean spectral shift of polarization maintaining and conventional single mode optical fiber.

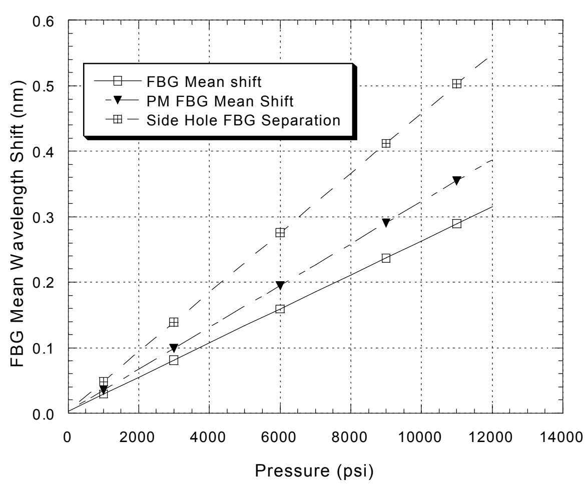

Figure 14 Peak to peak spectral shifts of side hole optical fiber (125 micron diameter fiber with 30 micron diameter side holes), mean spectral shift of polarization maintaining optical fiber and mean spectral shift of conventional single mode optical fiber to pressure

To illustrate the feasibility of measuring pressure and temperature at high speed 6 mm uniform fiber gratings were written into side-hole optical fiber. Because these fiber gratings are local and uniform the interpretation of spectral data is simpler. During one of the Russian DDT test runs for the 6 mm fiber grating only burn occurred, see Figure 15. These runs provide insight into the power of this novel diagnostic technique and its ability to extract measurements of pressure and temperature with changes on the order of a 5 to 10 nsec. The test run results are shown in Figure 16.

Figure 15 6 mm uniform fiber grating before ignition in a test pipe exhibiting burn only

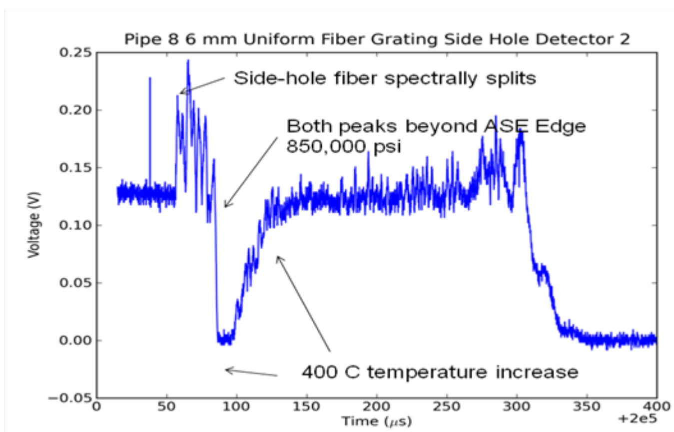

Figure 16 Test results for 6 mm uniform fiber gratings in burn only pipe

When ignition and burn begins, the spectral peaks of the uniform fiber grating split into two parts. This results in the amplitude spike at about 50 microseconds. When pressure continues to increase during burn the second peak is moved past the 1528 nm peak and falls off the 1524 nm edge corresponding to a pressure of about 850,000 psi when both peaks have moved over the edge. However as burn continues to occur the pipe and fiber grating heat up and temperature drives the second peak back over and through the 1528 nm peak which has a spectral width of 5 nm. *This corresponds to a temperature increase of the fiber grating of 400 C from 75 to 110 microseconds.* The temperature continues to increase but the read out system used for these tests does not have a second filter edge for measurements. It is clear that the combination of pressure and temperature allow the second spectral peak to stay in the flat region of the ASE spectrum until at about 225 microseconds there is oscillation in amplitude indicating that the second spectral peak has again been forced by pressure back to the 1528 nm peak and by 300 microseconds it is either being forced over the ASE spectral edge by pressure and or has reached the melting point of quartz at 1100 C.

As a second illustration of this technique, another 6 mm fiber grating written into side hole optical fiber was placed in the deflagration region of a Russian DDT test pipe (see the expansion region of the photo in Figure 10). The data has been filtered for high frequency content to make transitions easier to observe in Figure 17. Again there are pressure fluctuations resulting in splitting into two spectral peaks and increases in the overall amplitude of the light reflected from the fiber grating. As pressure levels rise first one peak and then the other move over the ASE light source spectral edge. This is followed by a large increase of temperature driving the spectrum reflected toward longer wavelengths and then a final increase in pressure that again dominates.

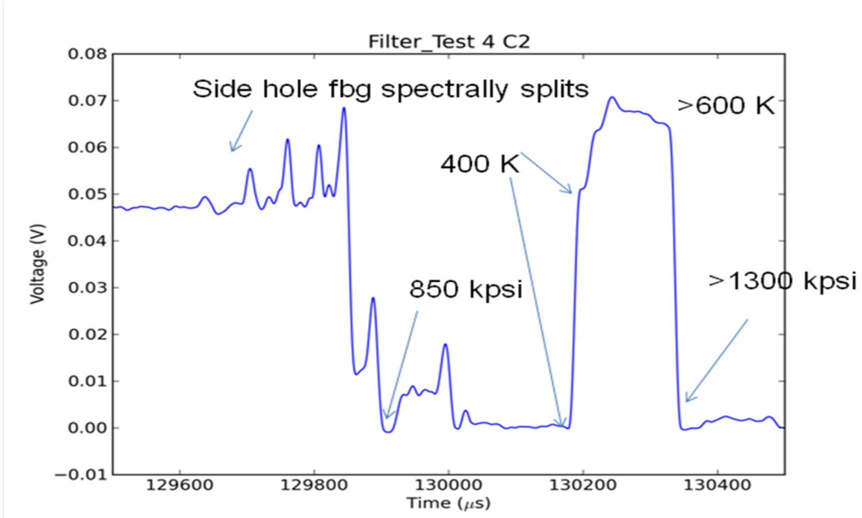

Figure 17 Side hole optical fiber placed in the deflagration region of a Russian DDT test using LX-14 as the energetic material, high frequency noise has been filtered

HIGH SPEED STREAKING OF FBG SPECTRAL RESPONSE WITH A COHERENT PULSE INTERROGATION METHOD TO 100 MEGAHERTZ

For a number of years, methods of *spectrally resolved* FBG measurements have been hampered by insufficient speeds for dynamic shock wave impact or high explosive detonation experiments. Methods based on frequency swept laser interrogation, or spectral reflectivity measurements using a linear arrayed detector mounted to spectrometer, still do not have the speed necessary for recording FBG response to high explosive or shock impact events. Typically, an interrogation rate faster than 10 MHz is required since the propagation speed of the high pressure wave disturbance is typically ranges from ~1 mm/μsec to as high as 15 mm/μsec. Fast sampling of the FBG is required if one is to successfully spatially (and spectrally) resolve the shock disturbance as it propagates along the FBG sensor. In 2014-15, we introduced a new coherent pulse interrogation technique that enabled full spectral interrogation of an FBG (and CFBG) at 100 MHz [13-15] by stroboscopic illumination of the FBG with a broadband modelocked short pulse laser followed by temporal streaking of the reflected pulse spectrum using a chromatic dispersive fiber. A high speed photodetector and transient digitizer records the reflected pulse spectrum at 100 MHz (i.e., every 10 ns), and a series pulses is recorded as a temporal waveform and stored in the digitizer memory. Rather than relying on the change of the integrated light return at the detector (as depicted in the approach shown in Figure 3), full spectral response of the FBG is strobed with the pulsed laser and a streaked record of shock position versus time along the FBG is obtained. The clear advantage of the streaked approach over the time integrated approach is when shock pressure conditions are relatively weak (i.e., < 3 GPa) compared to Young's modulus for silica fiber (E~70 GPa) based Bragg gratings as was shown in Ref. [15]. In experiments where we've demonstrated pressure conditions sufficiently low enough conditions are such that shock processing of the FBG does "destroy" the grating, the streaked approach may offer quantifiable measurements of strain or pressure along the section the FBG experiencing local stress as was done for uniform FBGs for point-like measurements as reported in [15].

The coherent pulse FBG interrogation system is illustrated in Figure 18. Modelocked 90-fs pulses from an Er fiber laser centered at 1560 nm with a 100 MHz repetition rate are launched into a single mode fiber (SMF28e) based system. The laser delivers broadband (1510 nm–1610 nm at the -10 dB points) pulses that are sufficient for illuminating FBGs of various types and wavelength channels. For these studies, single wavelength non-chirped FBGs between 1550 nm and 1560 nm were used. Laser pulses travel through a super wide band (S+C+L Band) 3-port circulator, illuminate the FBG sensor, and then exit port 3 to a 1x2 99:1 splitter. One percent of the return light from the FBG sensor was directed to a FBG interrogator volume grating based spectrometer with a 512-element InGaAs linear arrayed detector. The majority (99%) of FBG return light after the 1x2 splitter was sent along a chromatic dispersive element consisting of 5 km to 15 km spool of SMF28e fiber. The length of fiber used depended on the amount of time stretching and wavelength resolution desired since the stretched pulse translates into group delay wavelength mapping of the dispersed pulse into time for recording. After chromatic dispersion, time stretched pulse signals were amplified using a C-Band erbium doped fiber amplifier (EDFA) to boost the power losses introduced by the fiber spool to the few dBm level. A 35 GHz InGaAs photodetector converted the optical pulse train to electrical pulses for recording on a single channel of a 25 GHz, 50 GS/sec digitizing oscilloscope (Tektronix, Inc. DPO72004C). In addition to recording the optical time domain pulse train from the FBG sensor, a reference clocking signal directly from the laser is also recorded. The average dispersion constant for SMF28e fiber is 0.0167 ns/(nm-km). If a 10 km spool is used for chromatic dispersion, the effective spectral band between modelocked pulses (i.e., 10 ns inter-pulse period) is 60 nm. A sample spectrum for a 77-mm-long chirped FBG (chirp~ 3.353 mm/nm) is shown in Figure 18(a). The equivalent single-pulse streaked time domain spectrum of the grating recorded by the fast photodetector and digitizer after SMF28e fiber dispersion spool of 15 km is shown in Figure 18(b). The 100 MHz repetitive recording frequency of the FBG spectrum as shown in Figure 18(b) is done for as long as necessary to capture dynamics of the event.

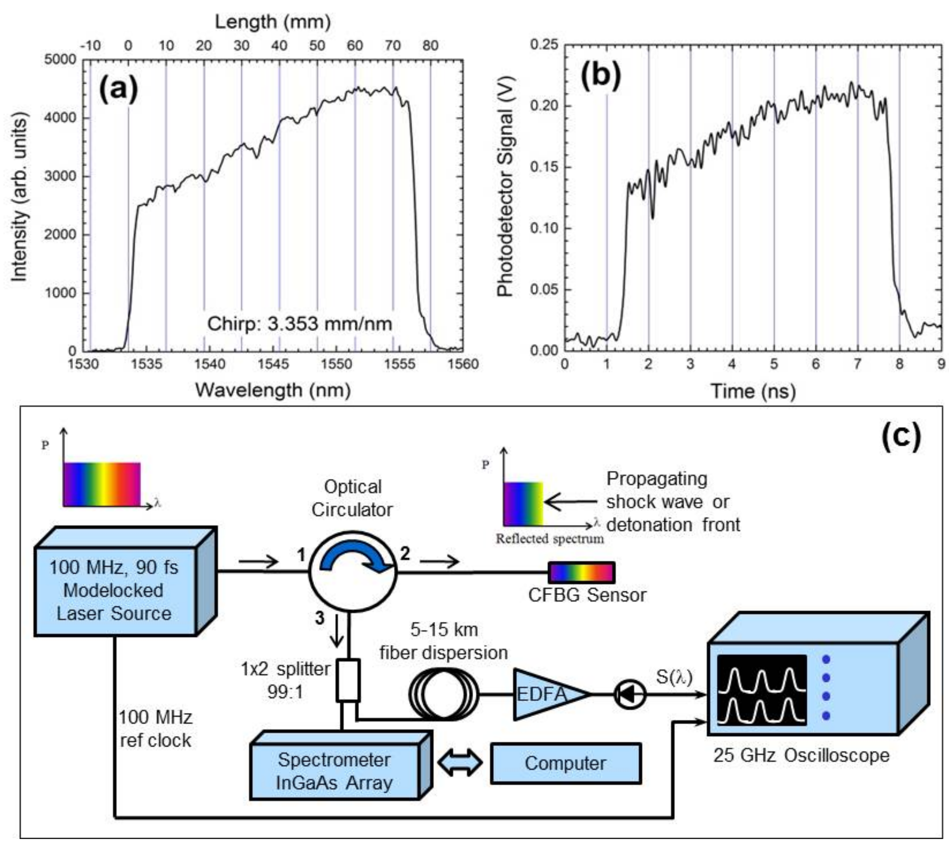

Figure 18. A typical 77-mm long linear chirped fiber Bragg grating (FBG) spectrum is shown in (a). It is centered at λ=1545 nm and has a bandwidth of $\Delta\lambda$~23 nm. The wavelength-to-length conversion factor (*i.e.*, chirp is given as 3.353 mm/nm) and was measured using a wavelength scanning optical backscatter reflectometer. The time domain equivalent spectrum is shown in (b) as measured by a single pulse from the oscilloscope trace using a setup as illustrated in (c) with 15 km of chromatic dispersive SMF28e fiber.

We demonstrate application of the streak based FBG sensing to measuring a detonation front sensing experiment. We return to a detection geometry that was performed and reported in a previous publication [10] using a hemispheric shaped high explosive (HE) where a chirped FBG was embedded between the outer surface of the explosive and a metal confinement case. The FBG chirp was 3.353 mm/nm, and a sample spectrum is the one shown in Figure 19. After initiation at the pole, the detonation front travels along a meridian line (longitude) in polar coordinates as initiated from the pole in a hemispheric-shaped PBX 9502 HE charge. The HE charge was tamped on the outside with a tantalum outer metal case, and there were two FBGs on the experiment are in between the HE and case and exit the device near the equator. The fibers were laid in a 77-mm-long by 228.6-μm deep groove that was machined into the outer surface of the HE. They were epoxied (M-Bond 200) in place before the outer metal case was mounted in contact with the HE. An illustration of the placement of two FBGs in the experiment is shown in Figure 19 showing a full azimuth angle between the gratings of 60°.

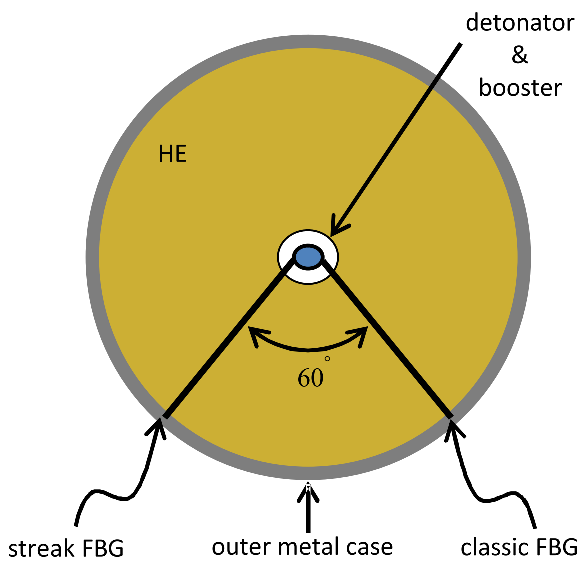

Figure 19. Polar view of experimental diagram showing placement of FBGs for detonation front measurement in PBX 9502 along a curved meridian (line of longitude). The hemispheric shaped HE charge is contained in an outer metal case, and two 77-mm-long CFBGs are epoxied between the HE and case. Azimuth angle between the two FBGs is 60 degrees. One FBG is recorded using the new streaking method, and the second FBG is measured using the classic method as diagrammed earlier in Figure 3.

Figure 20 shows the results from this hemisphere experiment. One FBG is recorded using the new streaking method, and the second FBG is measured using the classic method as diagrammed earlier in Figure 3. In Figure 20(a), the streaking method yields a 2D plot of wavelength versus time across the entire $\Delta\lambda$=23 nm band (centered at λ=1545 nm) of the chirped FBG that was shown in Figure 18. The time axis has a spectrum that is measured every 10ns, and at t=1.0 μsec the high explosive detonation front begins to cleanly "shock process" from the red to the blue portion of the grating. At t=10.4 μsec, the detonation front has completely consumed the entire grating, and the streaked spectrum signal at the photodetector reduces to zero. Comparison of the streaked FBG measurement to the classic recorded FBG is done by multiplying the wavelength axis of the 2D plot by the FBG chirp (3.353 mm/nm) and performing an edge detection analysis to the 2D image to determine the detonation front location. The results for comparison using both FBG sensing methods are shown in Figure 20(b). Clearly, both modes of FBG detonation front position measurements are in good agreement and demonstrate excellent simultaneous tracking yielding a linear slope fit to the data of 7.9 mm/μsec for the average detonation phase velocity.

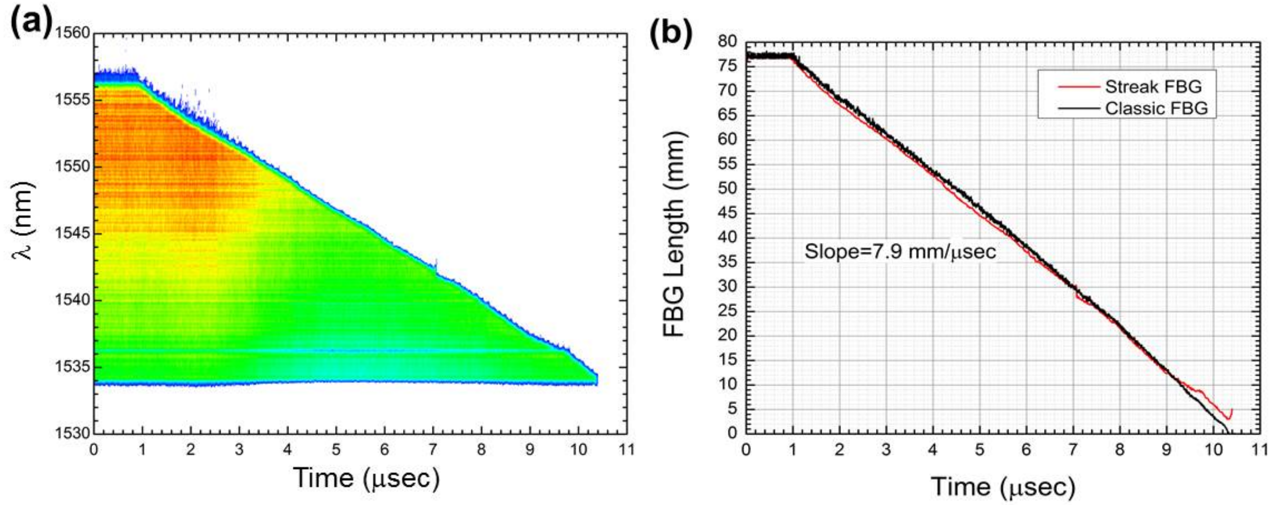

Figure 20. Two dimensional streaked spectrum versus time plot of chirped FBG that was fielded in the PBX9502 high explosive hemisphere experiment is shown in (a). After edge detection image processing, the streaked FBG results is compared to the non-streaked (classic) FBG results in (b) showing good agreement between the two methods of FBG detonation position detection. The average velocity is measured to be 7.9 mm/μsec.

A number of experiments at Los Alamos have been performed using the streaking based approach to FBG sensing and the reader is referred to Refs. [13-15] for examples that include shock and detonation front position sensing as well as dynamic pressure and strain measurements using single-color uniform FBGs under conditions when the FBG is not shock processed and destroyed and instead responds by spectral shifts according to the applied strain or pressure.

SUMMARY AND CONCLUSIONS

A new diagnostic tool continues to be developed to measure high speed events associated with the characterization of energetic materials. The technique allows unprecedented access to information that would be difficult or impossible to obtain using prior methods. This paper provides a brief overview of some of the tests demonstrating its capabilities and potential. More complete descriptions can be found in the references.

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